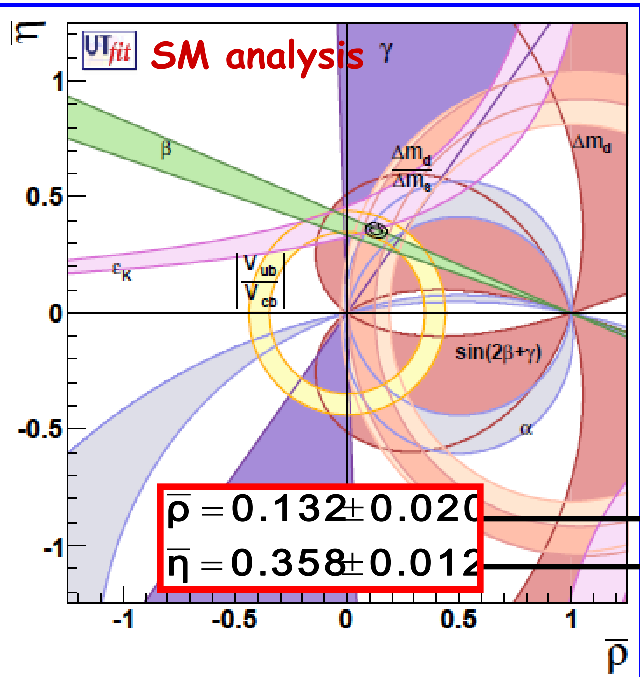
Coherent $D\bar{D}$ states at Super c/τ -factory

A.Bondar

1. CKM matrix and ϕ_3
2. Model-Independent Method
3. CLEO-c Results
4. D-mixing
5. Time integrated Method for D-mixing measurement
6. Conclusion

The UTA within the Standard Model



~16%

~ 3%

The experimental constraints:

$$\varepsilon_K, \Delta m_d, \left|\frac{\Delta m_s}{\Delta m_d}\right|, \left|\frac{V_{ub}}{V_{cb}}\right|$$ ⇒ relying on theoretical calculations of hadronic matrix elements

$$\sin 2\beta, \cos 2\beta, \alpha, \gamma (2\beta + \gamma)$$ ⇒ independent from theoretical calculations of hadronic parameters

overconstrain the CKM parameters consistently

The UTA has established that the CKM matrix is the dominant source of flavour mixing and CP violation

From a closer look

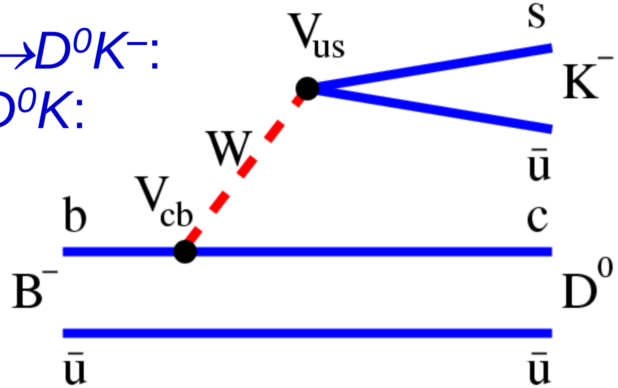
From the UTA (excluding its exp. constraint) → Prediction

	Prediction	Measurement	Pull
$\sin 2\beta$	0.771±0.036	0.654±0.026	2.6 ←
γ	69.6°±3.1°	74°±11°	<1
α	85.4°±3.7°	91.4°±6.1°	<1
$\lvert V_{cb}\rvert \cdot 10^3$	42.69±0.99	40.83±0.45	+1.6
$\lvert V_{ub}\rvert \cdot 10^3$	3.55±0.14	3.76±0.20	<1
$\varepsilon_K \cdot 10^3$	1.92±0.18	2.230±0.010	-1.7 ←
$BR(B \to \tau\nu) \cdot 10^4$	0.805±0.071	1.72±0.28	-3.2 ←

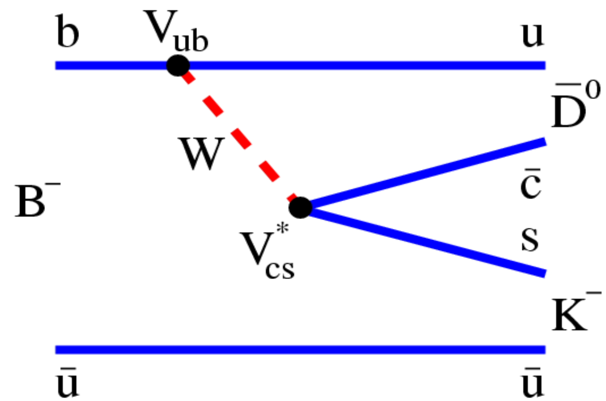
$B^+ \to D^0 K^+$ decay

CP violation enters the Standard Model as a complex phase ⇒ only observable in the interference. To measure φ_3/γ, use interference on V_{ub} and V_{cb} amplitudes:

$B^- \to D^0 K^-$:
$\to D^0 K$:



$\overline{B^-}$



$$A_1 \sim V_{cb} V_{us}^* \sim A\lambda^3$$

$$A_2 \sim V_{ub} V_{cs}^* \sim A\lambda^3 (\rho - i\eta) \sim e^{-i\varphi_3}$$

Amplitudes interfere if D^0 and $\bar{D}^0$ decay into the same final state $\left|D^0\right\rangle + re^{i\theta}\left|\overline{D}^0\right\rangle$

Relative phase: $\theta = -\varphi_3 + \delta$ ($B^- \to DK^-$), $\theta = \varphi_3 + \delta$ ($B^+ \to DK^+$)

includes weak (φ_3/γ) and strong (δ) phase.

Magnitude of CP violation is determined by the ratio of the two amplitudes:

$$r_B = \left|A(B^- \to D^0 K^-) / A(B^- \to \overline{D}^0 K^-)\right| = \left|\frac{V_{ub}^* V_{cs}}{V_{cb}^* V_{us}}\right| \times [\text{color supp.}]$$

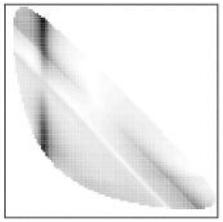
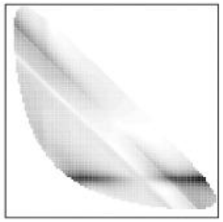
Dalitz analysis method

A. **Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003)**
A. Bondar, Proc. of Belle Dalitz analysis meeting, 24-26 Sep 2002.

$$\left|D^0\right\rangle + re^{i\theta}\left|\bar{D}^0\right\rangle$$

Using 3-body final state, identical for D^0 and $\bar{D}^0$: $K_s\pi^+\pi^-$.

Dalitz distribution density: $dp(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) \sim |f_D|^2 \, dm^2_{K_S\pi^+} \, dm^2_{K_S\pi^-}$

$$f_D(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) = \Bigg|$$  $$+ re^{i\delta \pm i\phi_3}$$  $$\Bigg|^2$$

(assuming CP-conservation in D^0 decays)

CPV can be observed as difference in the Dalitz distribution densities for D originated from B^+ and B^-

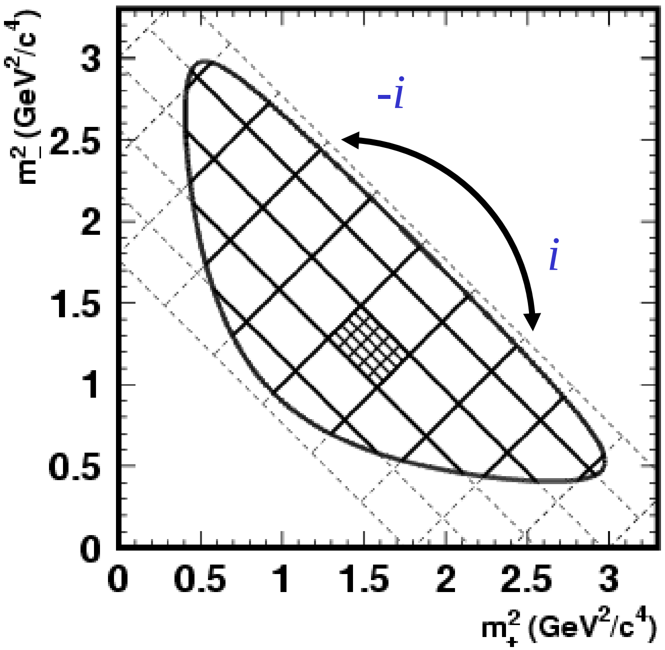
If $f_D(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})$ is known, parameters ($\varphi_3/\gamma, r_B, \delta$) are obtained from the fit to Dalitz distributions of $D \rightarrow K_s\pi^+\pi^-$ from $B^\pm \rightarrow DK^\pm$ decays

Need to know a complex form of the D^0 decay amplitude, but only $|f_D|^2$ is obtained from $D^* \rightarrow D\pi$

$\Rightarrow$ Need to use model description, model uncertainty as a result

Binned analysis

A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD 68, 054018 (2003)



Number of events in D^0-plot: K_i

Number of events in B-plot

$$M_i = K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(xc_i + ys_i)$$

Number of events in D_{CP}-plot

$$N_i = K_i + K_{-i} \pm 2\sqrt{K_i K_{-i}}\, c_i$$

$$c_i = \langle \cos\Delta\delta(\mathcal{D}) \rangle_{\mathcal{D}i} \qquad s_i = \langle \sin\Delta\delta(\mathcal{D}) \rangle_{\mathcal{D}i}$$

$$c_i = c_{-i},\, s_i = -s_{-i} \; and \qquad s_i^2 + c_i^2 \le 1$$

- c_i, s_i **can be obtained from B data (M_i) only** — **⇒ Very poor sensitivity**
- c_i **from D_{CP},** s_i **from B data** — **⇒ Poor sensitivity for y**

Dalitz: model-independent approach

A. Bondar, A. Poluektov, Eur.Phys.J. C 55, 51 (2008)

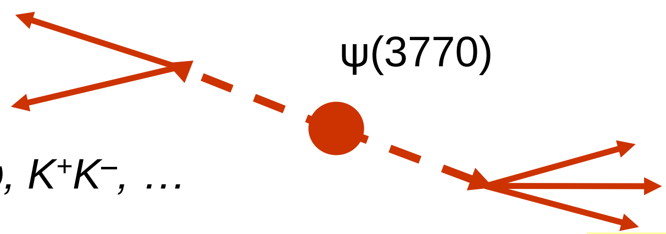
Model-independent way: obtain D^0 decay strong phase from $\psi(3770)\to D\bar{D}$ data

$$P_{B^\pm}(m_+^2, m_-^2) = |\, f_D + (x+iy)\bar{f}_D\,|^2 = P_D + r_B^2\overline{P}_D + 2\sqrt{P_D\overline{P}_D}[x_\pm C + y_\pm S]$$

$$P_D(m_+^2, m_-^2) = |\, f_D(m_+^2, m_-^2)\,|^2 \qquad \overline{P}_D(m_+^2, m_-^2) = |\, f_D(m_-^2, m_+^2)\,|^2$$

$$\left.\begin{aligned} x_\pm &= r_B\cos(\delta\pm\varphi_3) \\ y_\pm &= r_B\sin(\delta\pm\varphi_3) \end{aligned}\right\}$$ **Free parameters**

$$\left.\begin{aligned} C(m_+^2, m_-^2) &= \cos(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2)) \\ S(m_+^2, m_-^2) &= \sin(\delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2)) \end{aligned}\right\}$$ **Unknown, can be obtained from charm data at *ψ(3770)*:**



ψ(3770)

$D_{CP}\to K_S\omega$, K^+K^-, …

$D_{CP}\to K_S\pi^+\pi^-$:

$D_{CP}\to K_S\pi^+\pi^-$: $$P_{CP\pm}(m_+^2, m_-^2) = |\, f_D \pm \bar{f}_D\,|^2 = P_D + \overline{P}_D \pm 2\sqrt{P_D\overline{P}_D}\,C$$

$\psi(3770)\to(K_S\pi^+\pi^-)_D\,(K_S\pi^+\pi^-)_D$: $$P_{Corr}(m_+^2, m_-^2, m_+'^2, m_-'^2) = |\, f_D\bar{f}_D' - \bar{f}_D f_D'\,|^2 = P_D\overline{P}_D' + \overline{P}_D P_D' - 2\sqrt{P_D\overline{P}_D P_D'\overline{P}_D'}(CC' + SS')$$

Binned analysis: $(K_S\pi^+\pi^-)^2$

2 correlated Dalitz plots, 4 dimensions:

$$<N>_{ij} = K_i K_{-j} + K_j K_{-i} - 2\sqrt{K_i K_{-i} K_j K_{-j}}\,(c_i c_j + s_i s_j)$$

$$c_i = \frac{\int_{D_i} \sqrt{p_D \overline{p}_D} \cos(\Delta\delta_D(m_+^2, m_-^2))dD}{\sqrt{\int_{D_i} p_D dD \cdot \int_{D_i} \overline{p}_D dD}}$$

$$s_i = \frac{\int_{D_i} \sqrt{p_D \overline{p}_D} \sin(\Delta\delta_D(m_+^2, m_-^2))dD}{\sqrt{\int_{D_i} p_D dD \cdot \int_{D_i} \overline{p}_D dD}}$$

Can use maximum likelihood technique:

$$-2\log\mathcal{L} = -2\sum \log p_{Poisson}(N_{ij}, <N>_{ij}) \to \min$$

with c_i and s_i as free parameters.

For the same binning as in D_{CP}, number of bins is $\mathcal{N}^2$ (instead of $\mathcal{N}$),

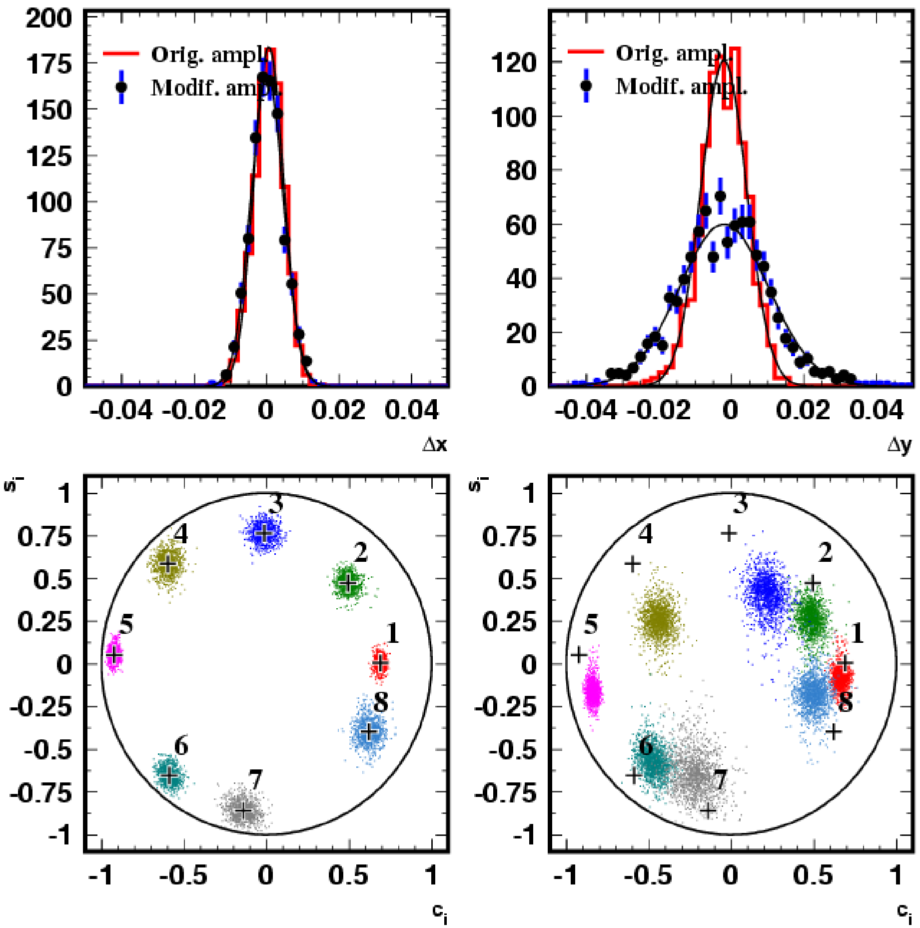
but the number of unknowns is the same.

With Poisson PDF, it's OK to have N_{ij}<1.

Can obtain both c_i and s_i.

Model-independent approach: toy MC

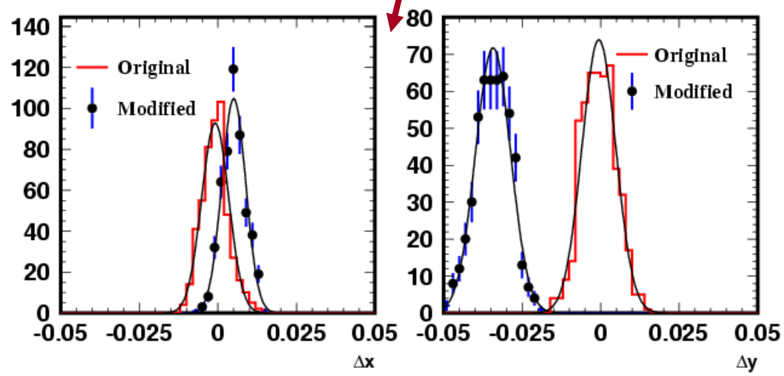
A. Bondar, A. Poluektov, Eur.Phys.J. C 55, 51 (2008)



Model dependence for 2x8 bins in $(K_s\pi^+\pi^-)^2$ case:

No bias when changing the model, but stat. error degrades.

Model dependence for 2x8 bins in D_{cp} case:



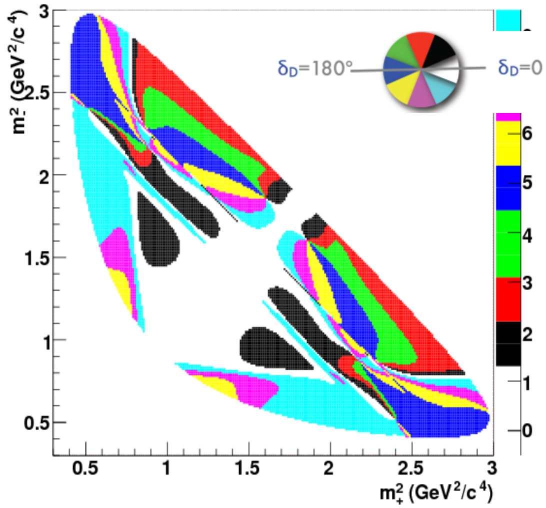
Model-independent approach

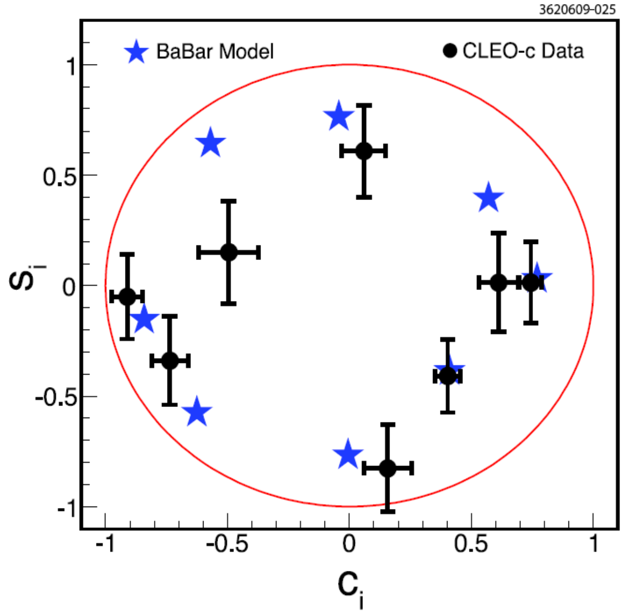
Introduce the binning of the phase space (i=-N, N). Number of events:

$$\langle N \rangle_i = h_B [K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}} (x c_i + y s_i)]$$

contains only the terms that can be obtained experimentally, does not depend on the amplitude structure inside the bin.

Optimal binning — stat. precision comparable to unbinned measurement





CLEO-c measurement: [arXiv:0903.1681, PRD 80 032002(2009)]. Expect 2-3° contribution
CLEO-c (NEW) [arXive:1010.2817]

D Mixing

- Improve precision of parameters of two mass eigenstates:

  $x_D = (m_2 - m_1)/\Gamma$; $y_D = (\Gamma_2 - \Gamma_1)/(2\Gamma)$;

  $|q/p|$ and $\phi_M = \mathrm{Arg}\,\{q/p\}$ ⟵ CPV parameters

  where

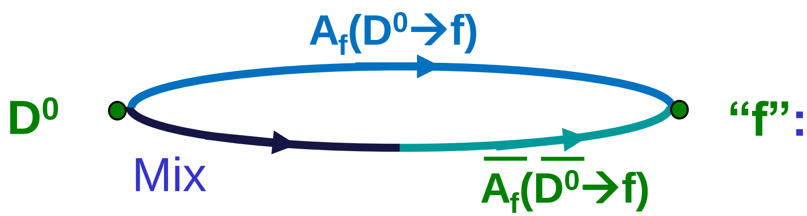
  $D^0 = p\,D_1 + q\,D_2$ and $\overline{D}^0 = p\,D_1 - q\,D_2$

- Search for CPV
- Examine whether CPV originates from the mixing ($p \neq q$), from decay ($\mathrm{Arg}\{A_f\} \neq \mathrm{Arg}\{\overline{A}_f\}$) or decay/mixing interference.

- Aim for precision in (x_D, y_D) of $\sim 10^{-4}$
- Allows ,measurement of asymmetries in D^0 and $\overline{D}^0$ parameters in various decay modes (direct CPV?)

Mixing Measurements

- All current measurements exploit interference between direct decays and decays through mixing:



Accessible to D or D
Kπ (WS),
point on DP, etc

Strong phase

$$\overline{A_f} = r_f e^{i\delta_f} A_f$$

- Time-dependence (no CPV, to 2nd order in *x* and *y*)

$$dN/dt \sim e^{-\Gamma t} \times [r_f^2 + r_f (y_D \cos \delta_f - x_D \sin \delta_f) \Gamma t + ¼(x_D^2+y_D^2)(\Gamma t)^2]$$

Direct decay — Interference — Decay through Mixing

- Interference term is approximately linear in x_D, y_D

  But r_f *and* δ_f *are, generally, unknown*

- So can usually only measure the rotated quantities

  $x'_D = x_D \cos \delta_f + y_D \sin \delta_f$ AND $y'_D = y_D \cos \delta_f - x_D \sin \delta_f$

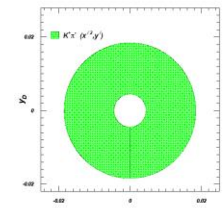
unless measurements of δ_f *from charm threshold are available.*

Mixing Measurements

x_D vs. y_D

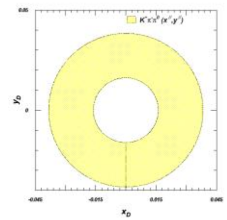
- WS decays $D^0 \rightarrow K^+\pi^-$:
  - □ δ_f unknown, $r_f^2 = R_{DCS}$ – measure $(x_D'^2, y_D')$

PRL 98,211802 (2007)



- WS decays $D^0 \rightarrow K^+\pi^-\pi^0$:
  - □ δ_f unknown, r_f from decay model – measure (x_D'', y_D'')

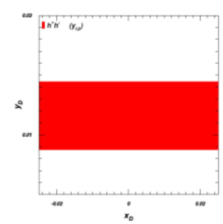
PRL 103:211801 (2009)



- "Lifetime" diff for $D^0 \rightarrow K^+K^-$ & $K^+\pi^-$:
  - – Measure y_{CP}

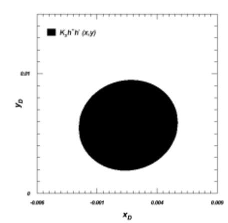
PRD 78:011105 (2008)

PRD 80:071103 (2009)



- "Golden channels" $D^0 \rightarrow K_s h^+h^-$
  - □ $\delta_f = 0$ - measure (x_D, y_D) directly,

Arxiv:1004.5053 (2010)
accepted by PRL

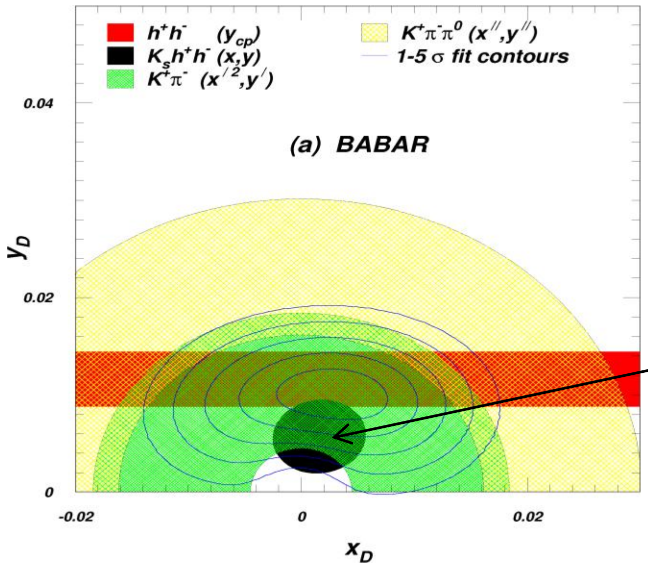


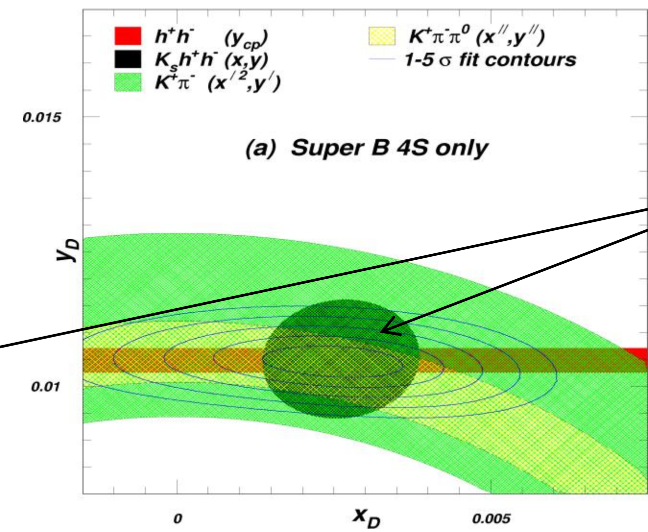
ALSO measures $|q/p|$ and $Arg\{q/p\}$! BUT

Introduces irreducible model uncertainty , IMU

Project to $75 ab^{-1}$@$\Upsilon(4S)$:

480 fb^{-1} → 75 ab^{-1}





Golden channels

Min. χ^2 fits (blue contours)

$$x_D = (3.01^{+3.12}_{-3.38}) \times 10^{-3}$$
$$y_D = (10.10^{+1.69}_{-1.72}) \times 10^{-3}$$

Unofficial average !!

→

$$x_D = (xxx^{+0.72}_{-0.75}) \times 10^{-3}$$
$$y_D = (xxx \pm 0.19) \times 10^{-3}$$

Uncertainties shrink: but are limited by the IMU (biggest effect on x_D)

Strong phase measurement from $\psi(3770)$ can greatly reduce this.

$$x_D \to xxx \pm 2.0 \times 10^{-4} \qquad y_D \to xxx \pm 1.2 \times 10^{-4}$$

Effect of D mixing in the quantum-correlated $D\bar{D}$ decays

[Z.Z.Xing, PRD 55, 196, (1997), D.Asner, W.Sun, hep-ph/0507238]

Effect of D mixing depends on C-parity of DD state.

For ($K_S\pi^+\pi^-$ vs $K_S\pi^+\pi^-$) events. C=-1:

$$N_{ij}'^{(asym)} = K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-i} K_j K_{-j}}(c_i c_j + s_i s_j) + O(x_D^2, y_D^2)$$

For C=+1:

$$\begin{aligned} N_{ij}'^{(sym)} = {} & K_i K_{-j} + K_{-i} K_j + 2\sqrt{K_i K_{-i} K_j K_{-j}}(c_i c_j + s_i s_j) + \\ & 2\sqrt{K_i K_{-i}} K_j (y_D c_i - x_D s_i) + 2\sqrt{K_i K_{-i}} K_{-j} (y_D c_i + x_D s_i) + \\ & 2\sqrt{K_j K_{-j}} K_i (y_D c_j - x_D s_j) + 2\sqrt{K_j K_{-j}} K_{-i} (y_D c_j + x_D s_j) + \\ & O(x_D^2, y_D^2) \end{aligned}$$

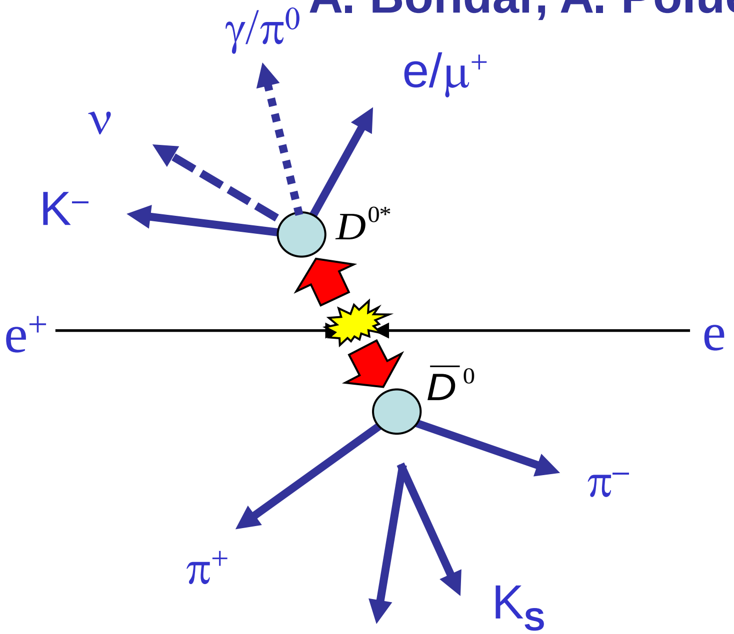
• $K_S\pi^+\pi^-$ - **Instrument for strong phase measurement in the hadronic D-meson decays**

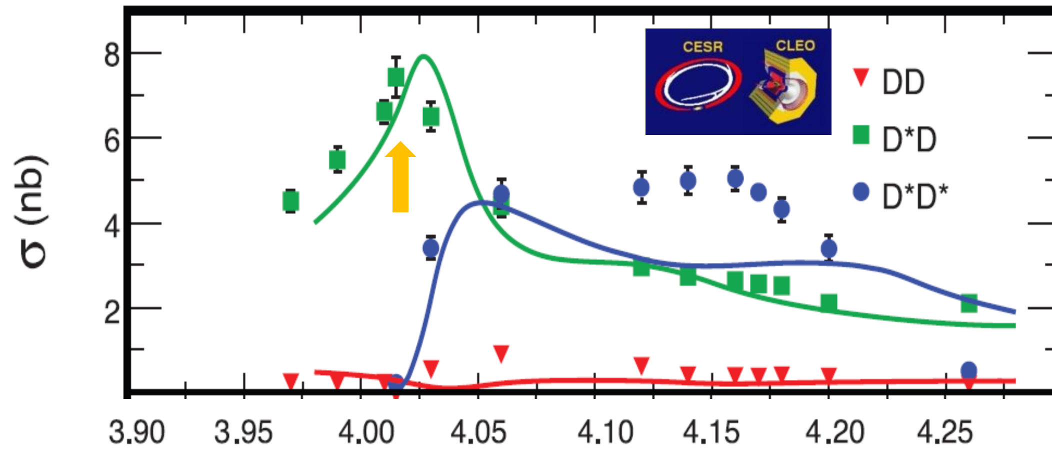
• **Difference in the** $K_S\pi^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$ **Dalitz plot distributions for even and odd DD states can be used for CPV and Mixing parameters measurement in the time integrated mode !**

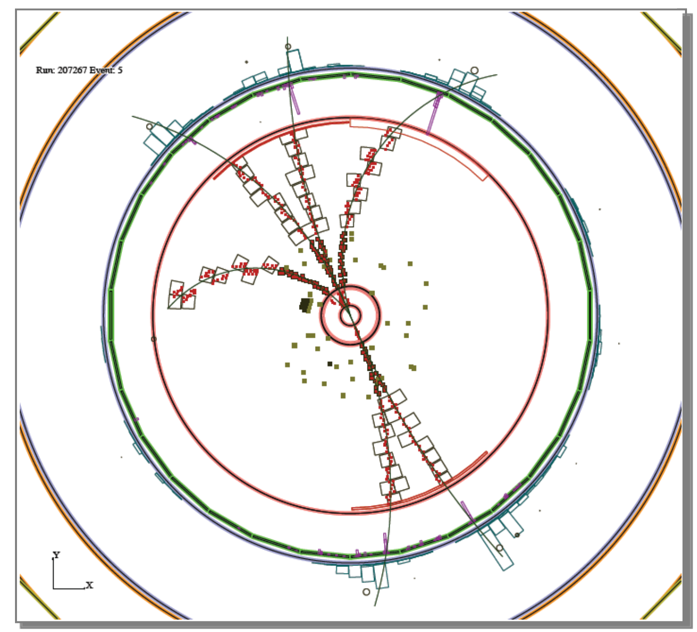
• **How create even and odd DD correlated states?**

D mixing in time integrated mode at c/τ Factory

A. Bondar, A. Poluektov, V. Vorobiev, PRD 82, 034033 (2010)



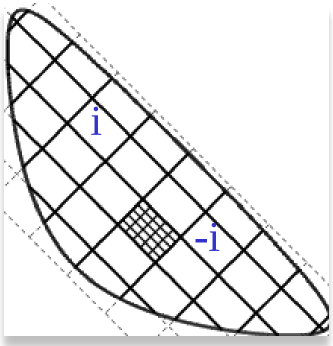




e^+e^- -> $K_S\pi^+\pi^-$ + $K^+\pi^-$ (CLEO-c)

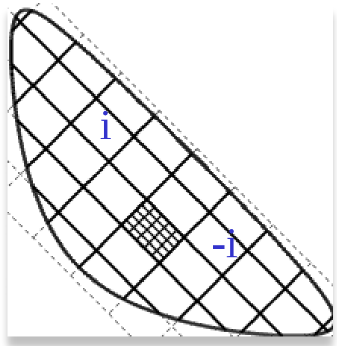
Pure DD final state ($E_{D^{(*)}} = E_{beam}$)
Equal to Ψ(3770) cross-section of DD
Low particle multiplicity ~ 6 charged part's/event
Good coverage to reconstruct ν in semileptonic decays
Pure $J^{PC} = 1^{--}$ initial state -
Flavor tags ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$),
Semileptonic (Xeν)

$D^{*+} \to D^0 \pi^+$



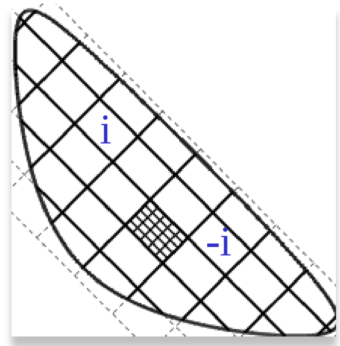
$$M_i = K_i$$

$B^- \to \tilde{D}^0 (K_S \pi^+ \pi^-) K^-$

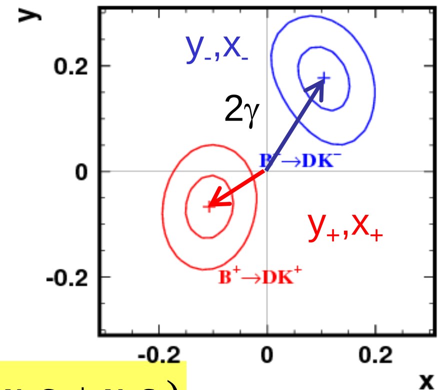


$$M_i = K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}} (x_- c_i + y_- s_i)$$

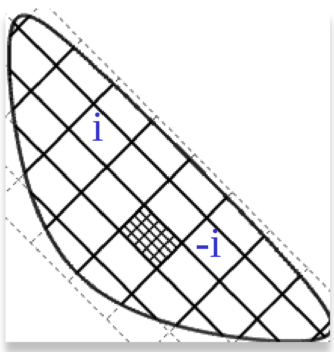
$B^+ \to \tilde{D}^0 (K_S \pi^+ \pi^-) K^+$



$$M_i = K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}} (x_+ c_i + y_+ s_i)$$

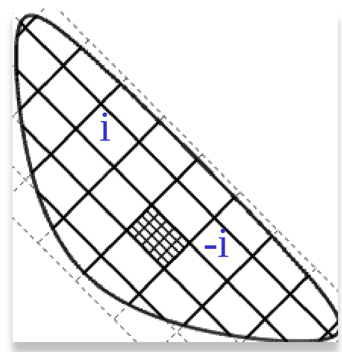


$e^+e^- \to D^0 D^{*0} \to (K_S \pi^- \pi^+)_D (K^+ l^- \nu)_D \pi^0$

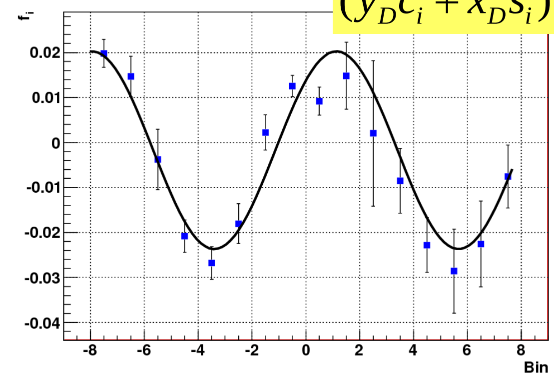


$$M_i^{(asym)} = K_i + O(y_D^2, x_D^2)$$

$e^+e^- \to D^0 D^{*0} \to (K_S \pi^- \pi^+)_D (K^+ l^- \nu)_D \gamma$



$$(y_D c_i + x_D s_i)$$



$$M_i^{(sym)} = K_i + 2\sqrt{K_i K_{-i}} (y_D c_i + x_D s_i) + O(y_D^2, x_D^2)$$

Data Samples (CLEO-c, 818 pb^{-1})

CLEO-c [arXiv:0903.1681, PRD 80 032002(2009)]

TABLE II: Single tag and $K^0_{S/L}\pi^+\pi^-$ double tag yields.

Mode	ST Yield	$K^0_S\pi^+\pi^-$ yield	$K^0_L\pi^+\pi^-$ yield
Flavor Tags			
$K^-\pi^+$	144563 ± 403	1447	2858
$K^-\pi^+\pi^0$	258938 ± 581	2776	5130
$K^-\pi^+\pi^+\pi^-$	220831 ± 541	2250	4110
$K^-e^+\nu$	123412 ± 4591	1356	-
CP-Even Tags			
K^+K^-	12867 ± 126	124	345
$\pi^+\pi^-$	5950 ± 112	62	172
$K^0_S\pi^0\pi^0$	6562 ± 131	56	-
$K^0_L\pi^0$	27955 ± 2013	229	-
CP-Odd Tags			
$K^0_S\pi^0$	19059 ± 150	189	281
$K^0_S\eta$	2793 ± 69	39	41
$K^0_S\omega$	8512 ± 107	83	-
$K^0_S\pi^+\pi^-$	-	475	867

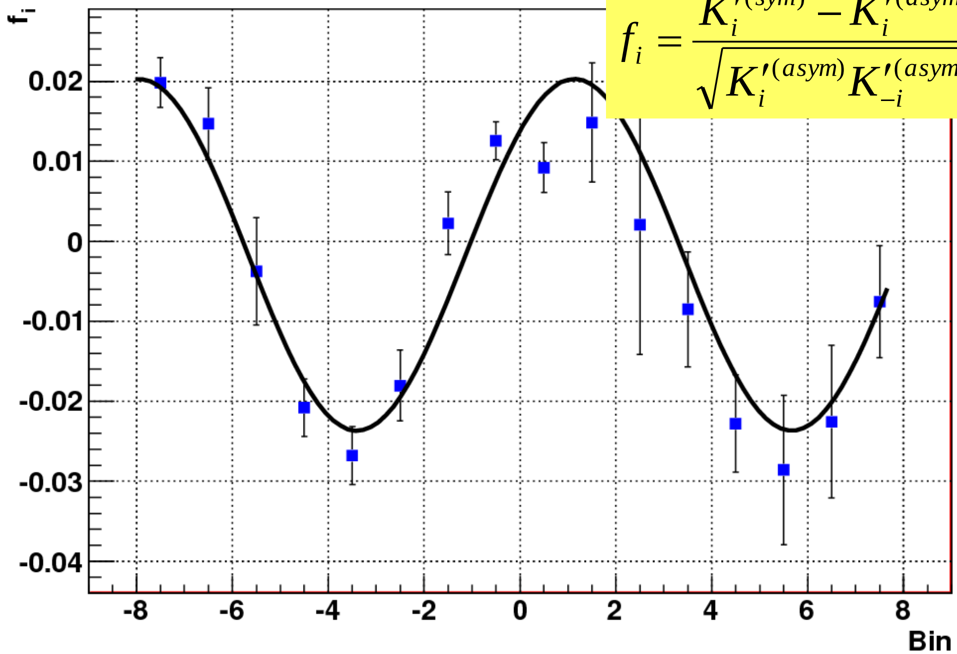
Expected Data yields for 1000 fb^{-1} (one year data taken at $L=10^{35}$):

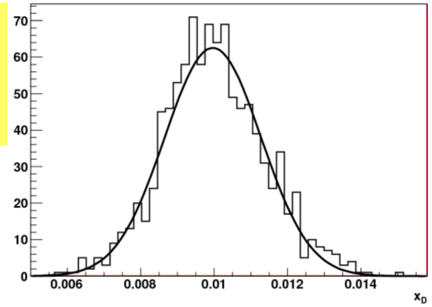
~ 3,5 10^6 $K_S\pi^+\pi^-$ vs $K^- l^+\nu$
~ 16 10^6 $K^+\pi^-\pi^0$ vs $K^- l^+\nu$ (3,5 10^4 WS)
~ 10,5 10^6 $K^+\pi^+\pi^-\pi^-$ vs $K^- l^+\nu$ (3,0 10^4 WS)
~ 8 10^6 $K^+\pi^-$ vs $K^- l^+\nu$ (3,0 10^4 WS)

~ 0,5 10^6 $K_S\pi^+\pi^-$ vs $K_S\pi^+\pi^-$
~ 2,7 10^6 $K_S\pi^+\pi^-$ vs $K^+\pi^-\pi^0$
~ 2,5 10^6 $K_S\pi^+\pi^-$ vs $K^+\pi^+\pi^-\pi^-$
~ 1,5 10^6 $K_S\pi^+\pi^-$ vs $K^+\pi^-$
~7,0 10^4 $K^+\pi^-\pi^0$ vs $K^+\pi^-\pi^0$

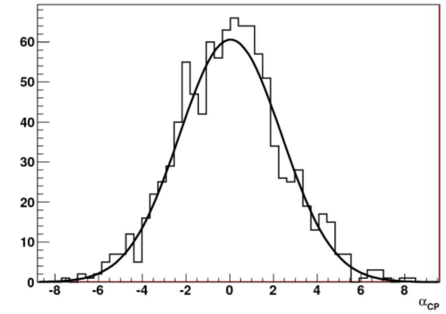
MC Sensitivity ($K_S\pi^+\pi^- + K^+l^-\nu$) 1ab^{-1}

$$f_i = \frac{K_i'^{(sym)} - K_i'^{(asym)}}{\sqrt{K_i'^{(asym)} K_{-i}'^{(asym)}}}$$

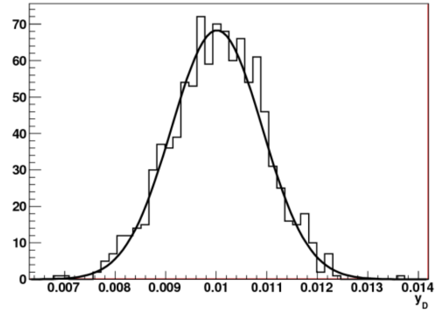




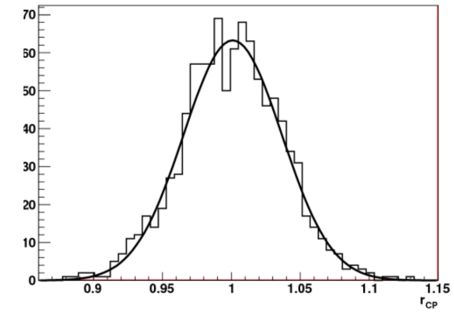
$\sigma(x_D)$=1.3 10^{-3}



$\sigma(\phi_{CP})$=2.3 ^{o}



$\sigma(y_D)$=0.9 10^{-3}



$\sigma(|q/p|)$=3.6 10^{-2}

If sensitivity of other states is comparable, the total statistical uncertainty should be 2-3 times better.

Conclusion

- **Dalitz analysis is most sensitive method for φ_3/γ measurements now**
- **Combining all B-factory results, there is strong evidence of CP violation in $B \to DK$. Good agreement between different measurements, both in r_B and γ/φ_3**
- **Future φ_3/γ statistical precision will be limited by model uncertainty. Model-independent Dalitz analysis using charm data from Super c/t-factory will allow to achieve the order of one degree accuracy**
- **Dalitz method can be extended to D-mixing measurements in the time integrated mode. Sensitivity of the Super C/τ – factory can be competitive to Super B-factories sensitivity**